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Diode-pumped continuous-wave laser operation of co-doped (Ho,Tm):$KLu(WO_4)_2$ monoclinic crystal

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ABSTRACT

We report on room-temperature continuous-wave laser operation at 2.06 μm in co-doped (0.5 at% Ho, 5.0 at% Tm):$KLu(WO_4)_2$ monoclinic crystal pumped at 805 nm by a commercially available AlGaAs diode laser stack. A maximum output power of 93 mW and a slope efficiency of 14.7% with respect to absorbed power were achieved.

1. Introduction

Development of compact eye-safe solid-state lasers in the near infrared region based on rare earth lanthanide ions is of special interest in recent years because of their vast scientific and technological applications. For instance the Ho^{3+} (Ho) ion which emits slightly above 2 μm has potential applications in the field of remote sensing, medical treatments and as a pump source for mid-IR Optical Parametric Oscillators (OPOs) [1]. The main drawback of the trivalent Ho ion is that it does not exhibit suitable absorption bands for efficient pumping. In order to overcome this drawback many researchers used Tm^{3+} (Tm) ion as sensitizer in different hosts due to the possibility to pump the co-doped system with commercially available AlGaAs laser diodes near 800 nm [2–5].

Concerning the host, potassium lutetium double tungstate with the chemical formula $KLu(WO_4)_2$ (hereafter KLuW) [6,7] belongs to the family of the monoclinic potassium double tungstates which stand out for their very high absorption and emission cross-sections when doped with lanthanide active ions and their capability to accept high doping levels without fluorescence quenching effects. Recently KLuW has been shown to be the most suitable such host for Tm and Yb active ions and moderate power levels, around 10 W in continuous-wave (CW) regime. In the case of Yb:KLuW [8], up to 11 W output power has been achieved under fiber-coupled diode pumping (N.A. = 0.22), with an absorbed power of 16.2 W corresponding to a slope efficiency of 80%. For Tm:KLuW [9] 10.4 W output power has been achieved. Here the pumping architecture is rather different. The authors in [9] used a CS-mount diode laser and launched up to 34.2 W achieving a maximum slope efficiency of 43% (with respect to the incident power) in a special designed six-passes pumping scheme.

In this work, we achieved for the first time to our knowledge diode-pumped continuous wave (CW) laser operation of co-doped (Ho,Tm):KLuW crystal.

2. Experimental details

Macro defect free single-crystal with high optical quality with a doping ratio of 0.5 at% Ho, 5 at% Tm:KLuW was grown by the Top Seeded Solution Growth Slow-Cooling method (TSSG-SC) using $K_2W_2O_7$ as a solvent. The methodology of growth can be found elsewhere [10]. Information on the spectroscopic properties of (Ho,Tm):KLuW crystals can be found in our previous work [11,12] where we obtained lasing under Ti:sapphire pumping. The Tm ion

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shows maximum absorption cross-section of 5.2×10^{-20} cm^2 at 802 nm for light polarization with the electric field (E) parallel to the $\boldsymbol{N}_m$ principal optical axis ($E//\boldsymbol{N}_m$). In order to obtain the gain cross-section curves of Ho, emission cross-section of Ho was calculated by the reciprocity method [13]. For the sake of brevity only gain curves for $E//\boldsymbol{N}_m$ are presented in Fig. 1 which is sufficient to understand the laser emission reported below. The calculated gain curves of Ho for several inversion levels (β) in the 1900–2100 nm range show a maximum centered at 2060 nm.

The laser experiment was carried out with a 2-mirror hemi-spherical resonator (see Fig. 2). M1 is the plane pump mirror, highly transmitting ($>98\%$) at the pump wavelength and highly reflecting in the 1800–2100 nm range. M2 is the concave output coupler with radius of curvature RC=50 mm and transmission (T_{oc}) 1.5% ($\pm 0.5\%$), 3.0% ($\pm 1\%$), 5.0% ($\pm 1.0\%$), and 9.0% ($\pm 1.0\%$) in the 1820–2050 nm range.

The pump source was a fiber coupled AlGaAs laser diode stack (NA=0.22) emitting at 805 nm from Lumix (model no: LU808C045-E). The pump was focused using the lens assembly L1 (consisting of a collimating and a focusing lens) to a beam diameter of the order of 200 μm. The AR coated active medium used was a N_g cut (0.5 at% Ho, 5 at% Tm):KLuW crystal which showed best performance in experiments with Ti:sapphire laser pumping [12]. These doping levels correspond to ion density in this crystal of 5.291×10^{19} cm^{-3} (Ho) and 2.301×10^{20} cm^{-3} (Tm). Such values were measured for proper calculation of concentration of active ions. The thickness of the active element was 3 mm and the aperture size was 3×3 mm^2. The crystal was located as close as possible to the pump mirror. We used indium foil at the top and bottom surfaces of the crystal to ensure better contact with the copper holder which was water cooled to 16 °C for dissipation of heat.

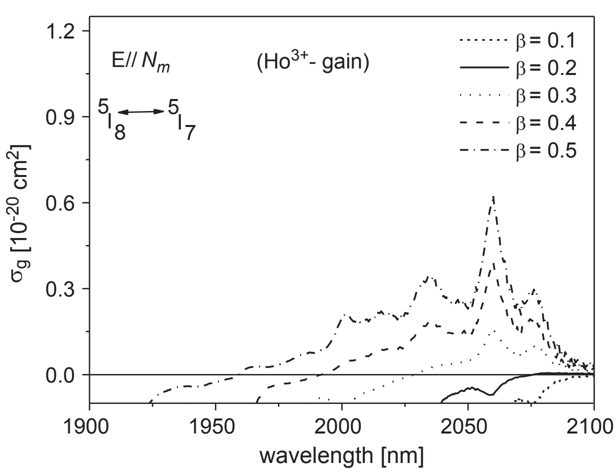

Fig. 1. Calculated gain cross-section curves of Ho for $E//\boldsymbol{N}_m$ in the (Ho,Tm):KLuW crystal.

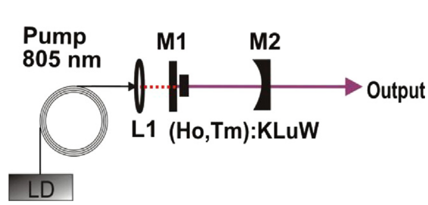

Fig. 2. Cavity setup of the (Ho,Tm):KLuW laser. LD—laser diode which is fiber coupled (NA=0.22) emitting at 805 nm; L1—lens assembly consisting of collimating and focusing lens, imaging ratio1:1, 200 μm beam diameter; M1—plane pump mirror; M2—concave output coupler with radius of curvature −50 mm; Ho,Tm: KLuW crystal—thickness 3 mm.

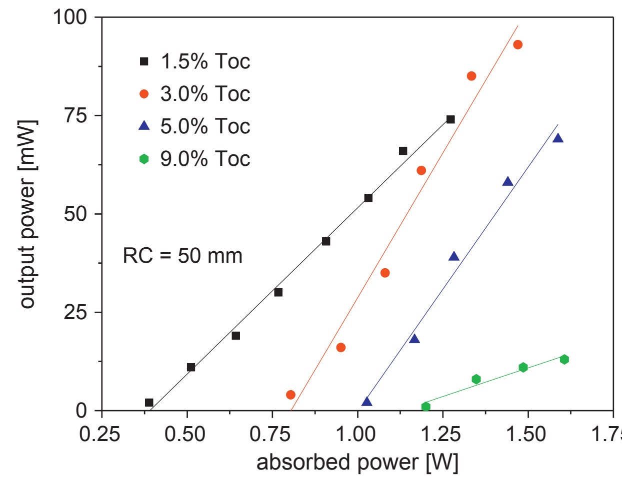

Fig. 3. Output power versus absorbed pump power of the (0.5 at% Ho5 at% Tm): KLuW laser for different T_{oc}.

Table 1
Summary of the laser characteristics for different T_{oc}.

T_{oc} [%]	Maximum output power [mW]	Slope efficiency [%]	Wavelength [nm]
1.5	74	8.5	2078, 2063
3.0	93	14.7	2062
5.0	69	12.4	2062
9.0	13	2.9	2062

3. Results and discussion

CW laser operation on the $^5I_7 \rightarrow {}^5I_8$ transition of Ho was realized for all the output couplers. The output from the (Ho,Tm):KLuW laser was always linearly polarized with $E//N_m$ although the pump is not polarized. We measured the output power as a function of the incident power for a physical cavity length of 50 mm. For the calculation of the slope efficiency, we used the measured value of the absorption without lasing (68%, taking into account a second pump pass through the reflection of the output mirror). A maximum output power of 93 mW was achieved for an absorbed power of 1470 mW. Fig. 3 and Table 1 summarize the input–output characteristics of the (0.5 at% Ho, 5 at%Tm): KLuW laser for different output coupling T_{oc}.

The T_{oc}=3% output coupler gave maximum output power and highest slope efficiency (14.7%) and in this case, we measured the quality of the beam by the knife-edge method, resulting in $M_x^2 = M_y^2 = 1.2$

The laser wavelength was at 2062 nm for the T_{oc}=3%, 5%, and 9% output couplers, it was longer only for the lowest 1.5% output coupling 1.5%@2060 nm (1.7%@2080 nm) (Fig. 4), as could be expected for a three-level system.

It is interesting that for T_{oc}=1.5% dual wavelength operation occurs which can be attributed solely to the Ho ion. This could be explained with the help of the gain curves as shown in Fig. 1. For low inversion levels the gain exhibits two maxima which are comparable. Thus simultaneous oscillation from different Stark sub-levels of the same ($^5I_7$) manifold is possible. Tm lasing, as in the case of using Ti:sapphire laser as a pump source [14] was not observed in the present experiment, presumably related to the lower pump intensity and Tm inversion level achieved.

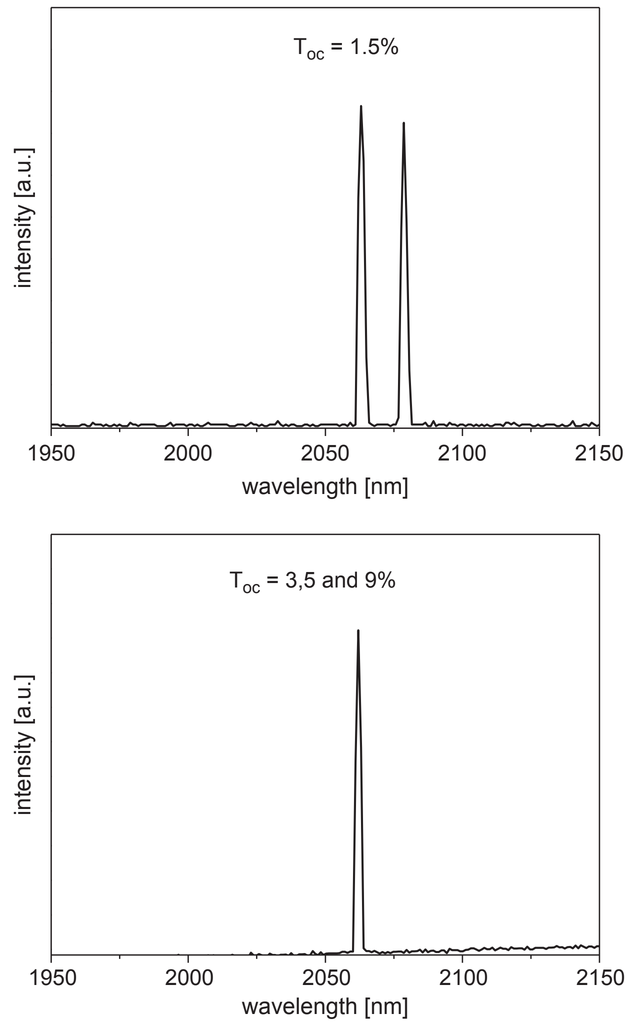

Fig. 4. Typical emission spectra of the (Ho,Tm):KLuW laser for different output coupling T_{ocs}.

4. Conclusions

In summary, we have demonstrated the diode pumped continuous wave laser action in the (Ho,Tm):KLuW system operating at 2.06 μm and studied several transmissions of the output coupler achieving a maximum output power of 100 mW.

The present work represents additional knowledge to what is an extended work on room temperature laser operation of (Tm, Ho)-doped laser crystals like, garnets, fluorides and vanadates [15]. In our opinion, the (Ho,Tm):KLuW system should be improved with a special cooling system design to increase the output power and efficiency of the laser, such as the use of a cryogenic chamber. This is what we plan next.

Acknowledgments

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